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# Path Loss Models for Indoor Off-Body Communications at 60 GHz

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***Abstract*—In this paper we present some empirically obtained path loss models for 60 GHz line of sight (LOS) and non-LOS (NLOS) off-body communications within indoor environments. In particular, we considered signal propagation from a chest worn millimeter wave transmitter and a hypothetical base station in both a laboratory and seminar room. It was found that shadowing of the direct signal path caused by the wearer's body increased the path loss by more than 20 dB at the reference distance (1 m). The fluctuation of the path loss at each of the measurement locations is modeled as a zero mean Gaussian distributed random variable and a linear relationship between the separation distance and standard deviation of the path loss variation is deduced.**

***Keywords—body centric communications; fading; millimeter wave communications; shadowing; path loss; wearables***

## I. INTRODUCTION

Recently, renewed interest has been generated towards the use of millimeter-wave (mm-wave) technologies for body centric and wearable systems [1-5]. Advancements in this area mean that it will soon be feasible to use operating frequencies in the 59-66 GHz range to provide high bandwidth capabilities for these applications. Operating wearable systems within this part of the mm-wave spectrum will be attractive for many reasons, not least due to the small size of antenna that can be used [4], the lower interference and much greater frequency reuse that can be achieved over smaller areas [2] compared to competing microwave technologies.

The characteristics of the on-body channel at 60 GHz have been studied in [4]. Here it was shown that the choice of antenna polarization is of great importance and its impact is significantly influenced by the separation distance between the antenna and the body. Similarly an off-body propagation model at 60 GHz was developed using theory in [5] and validated using empirical measurements. In [5] the path gain was considered for varying angular orientations of a human subject while maintaining a fixed separation distance between the transmitter and receiver. Alternatively, in this paper we focus on the path loss due to differing transmitter-receiver separation in off-body channels, determining new models for both line of sight (LOS) and non-LOS (NLOS) conditions in a number of indoor environments.

## II. MEASUREMENT SYSTEM AND PATH LOSS EXPERIMENTS

The experiments conducted in this study were all carried out in the European (59-66 GHz) unlicensed Industrial, Scientific and Medical (ISM) band at an operating frequency of 60 GHz. The measurement system consisted of a Hittite HMC6000LP711E millimeter wave transmitter (TX) module and Hittite HMC6001LP711E millimeter wave receiver (RX) module, both containing on-chip, low profile antennas. The in package antennas offer +7.5 dBi gain, with a maximum Equivalent Isotropically Radiated Power (EIRP) of +23.5 dBm. For the path loss experiments conducted here, the TX unit was configured to deliver a continuous wave signal at the maximum EIRP. The complex baseband output of the RX module was connected to port 1 of a Rhode and Schwarz ZVB-8 vector network analyser (VNA) which was configured to collect samples of the $b_1$ wave quantity at a sample rate of 470 Hz.

The 60 GHz RX, which acted as a hypothetical mm-wave base station, was positioned on a wooden stand at a height of 1.45 m from the floor such that the antenna was in a vertically polarized orientation. The 60 GHz TX was then positioned on the central chest of adult male at a height of 1.25 m, so that the antenna was parallel to the body surface. The TX was secured to a harness worn by the test subject using a small strip of Velcro® (approximately 6 mm from the body surface). Two different measurement environments were considered in this study, namely a medium-sized laboratory room (4.75 m x 9.14 m) and a larger seminar room (7.92 m x 12.58 m). Both locations were situated within the Institute of Electronics, Communications and Information Technology (ECIT) at Queen's University Belfast in the United Kingdom. They were constructed from metal studded dry walls with a metal tiled floor covered with polypropylene-fiber, rubber backed carpet tiles, and metal ceiling with mineral fiber tiles and recessed louvered luminaries suspended 2.70 m above floor level. The laboratory is situated on the 2nd floor of the ECIT building and contained a number of chairs, boxes, lab equipment, metal cabinets and also desks constructed from medium density fibreboard. The seminar room, which is situated on the 1st floor of the ECIT building, contained a large number of chairs, desks, a projector and a white board. It also featured an external facing boundary wall constructed entirely from glass with some metallic supporting pillars. It should be noted that both areas were unoccupied for the duration of the measurements.

In this study we considered LOS channel conditions where the test subject was oriented such that maximum gain of the radiation patterns of the TX and RX were co-aligned. For the NLOS channel measurements the test subject rotated his body through 180° so that the direct signal path was now obstructed by his torso. For all of the scenarios investigated in this study, 1500 samples of the 60 GHz off-body channel were collected. In the laboratory environment, path loss measurements were

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collected for increasing separation of the body worn TX and the hypothetical mm-wave base station from 1 m to 7 m in steps of 1 m. Due to the larger dimensions of the seminar room, it was possible to collect path loss data over a greater distance. In this case the channel acquisitions were performed from 1 m to 9 m also in steps of 1 m. All of the measurements were conducted while the user remained stationary. The average noise floor was determined in both environments before the experiments and was found to be -79.8 dBm. Correspondingly, the lowest recorded sample used in the data analysis was found to be -78.1 dBm, which was recorded in the laboratory environment.

## III. Results

The log-distance path loss, $P$, measured in decibels between a transmitter and receiver separated by a distance $d$ may be written as

$$P[\mathrm{dB}] = P(d_0) + 10n\log_{10}(d/d_0) + X \tag{1}$$

were $P(d_0)$ represents the path loss at the reference distance ($d_0$ = 1 m), $n$ is the path loss exponent and $X$ is a random variable (RV) which represents the fluctuation of the path loss about the mean path loss level which in this case was assumed to be a zero mean, Gaussian distributed RV. The channel data obtained at each of the measurement locations was logarithmically transformed into its signal power and the path loss subsequently calculated. Linear regression was then performed in MATLAB to obtain estimates for $P(d_0)$ and $n$. In this study, $X$ was determined independently at each measurement location by firstly removing an estimate of the mean path loss and then finding the standard deviation, $\sigma$, of the resultant data set.

Table I presents the estimated path loss model parameters for the both environments. For LOS conditions in the laboratory, the estimated path loss at the reference distance was found to be 33.1 dB, however when the test subject's body obstructed the direct signal path (i.e. NLOS), the path loss was found to increase by 20 dB [Figs. 1(a) and (b)]. It is likely that the high metallic content of the floor, ceiling and numerous objects within the room would have generated some multipath components which in turn would have mitigated the shadowing induced by the test subject's body on the link. For the LOS scenario, $n$ was found to be less than 2 which is generally anticipated for free space propagation. This was expected due to the directive nature of the antenna radiation patterns which offered +7 dBi gain. In the more spatial seminar room, the impact of body shadowing on the off-body link was more pronounced. Here the path loss at the reference distance increased by more than 30 dB. In both environments for NLOS channel conditions, the path loss exponents were quite low, showing that over the short ranges considered here, the path loss does not overly increase with distance when the wearer's body obstructs the signal, instead body shadowing is the predominating factor.

To construct a relationship between the variation of the path loss about its mean level for differing TX-RX separation distances, an equation of the form $\sigma = md + C$ (where $m$ is the gradient of the line, $d$ is the separation distance as before and $C$ is the vertical axis intercept point) was fitted to the parameter estimates (Table I). As an example, Fig. 1(c) shows the variation of the $\sigma$ parameter for the laboratory environment. Most notably in this environment, the $\sigma$ parameter is observed to increase with distance for both LOS and NLOS conditions. As an example of the distribution fitting, Fig. 1(d) shows the cumulative distribution function (CDF) of the Gaussian distribution fitted to the empirical data obtained at the 3 m position for both the LOS and NLOS scenarios in the seminar room.

TABLE I. Path Loss Model Parameter Estimates

| Scenario | $P_0$[dB] | $n$ | $\sigma = md + C$ |
|---|---|---|---|
| **Laboratory LOS** | 33.1 | 1.23 | $m$ = 0.25, $C$ = 0.79 |
| **Laboratory NLOS** | 54.5 | 1.27 | $m$ = 0.56, $C$ = 3.42 |
| **Seminar Room LOS** | 33.3 | 2.34 | $m$ = 0.69, $C$ = 0.19 |
| **Seminar Room NLOS** | 63.8 | -0.2 | $m$ = -0.29, $C$ = 6.25 |

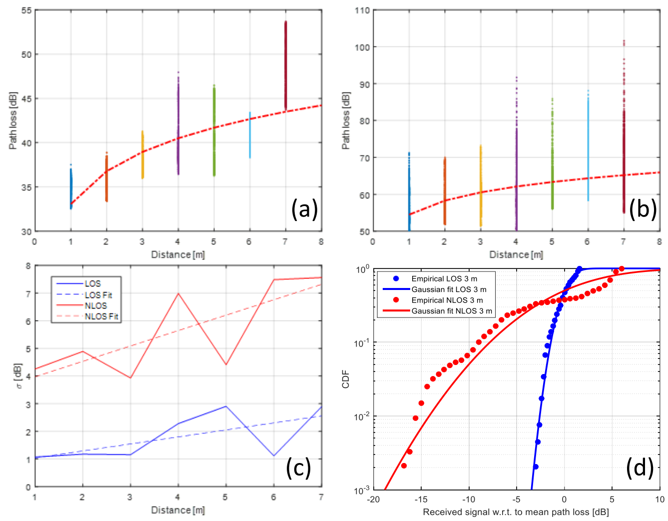


Fig. 1 Path loss for (a) LOS and (b) NLOS, (c) variation of the $\sigma$ parameter of the Gaussian distribution with distance and (d) example of model fitting for 3 m separation while the test subject was in LOS and NLOS in the seminar room.

## IV. Conclusion

A number of new path loss models for 60 GHz off-body communications within indoor environments have been presented. The standard deviation of the path loss fluctuation has been modeled as a function of the transmitter-receiver separation distance so that the results presented here can be easily reproduced.

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